REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
25-07-2012

2. REPORT TYPE
Conference Paper and Briefing Charts

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE

Experimental Assessment of Double Langmuir Probe Analysis Techniques in a Hall Thruster Plume

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Brown, D.L.; Beal, B.E.; Blakely, J.M.

5d. PROJECT NUMBER

5f. WORK UNIT NUMBER
33SP0708

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/RZSS
9 Antares Road
Edwards AFB CA 93524-7401

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/RQR
5 Pollux Drive
Edwards AFB CA 93524-7048

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S NUMBER(S)
AFRL-RZ-ED-TP-2012-232

12. DISTRIBUTION / AVAILABILITY STATEMENT

Distribution A: Approved for public release; distribution unlimited. PA# 12624.

13. SUPPLEMENTARY NOTES
48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit and 10th International Energy Conversion Engineering Conference, Atlanta, GA, 29 July – 2 August 2012.

14. ABSTRACT
A recent theoretical study of double Langmuir probes led to development of improved analytical techniques that account for probe electrode sheath expansion in a low-temperature plasma environment. The proposed technique is based on analytical curve fitting to Laframboise's results, which enables double probe measurement of electron temperature and plasma density over a wide range of densities without advance knowledge of the probe radius relative to Debye length. In this investigation, the method was evaluated by comparing plasma properties from three double Langmuir probes of varying electrode diameter. Far-field measurements of a Hall thruster plume were conducted with each probe at two facility background pressures. Plasma characteristics were calculated using the proposed analytical technique, and compared to orbital motion limited and thin-sheath analyses in regions of the plume where these methods are valid. Results revealed equivalent plasma properties from each double probe geometry when using the proposed double probe analysis methodology, indicating the electrode sheath expansion is accounted for. Calculated plasma densities and electron temperatures were consistent with standard analysis techniques. These findings support the proposed double probe analysis method for examination of plasma properties over a wide span of the far-field plume using a fixed Langmuir probe design and a single analysis technique.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Daniel L. Brown
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
Unclassified	**Unclassified**	**Unclassified**	SAR	28	N/A

Experimental Assessment of Double Langmuir Probe Analysis Techniques in a Hall Thruster Plume

D. L. Brown[1] and B. E. Beal[2]
U.S. Air Force Research Laboratory, Edwards Air Force Base, CA 93524

J. M. Blakely[3]
ERC, Inc., Edwards Air Force Base, CA 93524

A recent theoretical study of double Langmuir probes led to development of improved analytical techniques that account for probe electrode sheath expansion in a low-temperature plasma environment. The proposed technique is based on analytical curve fitting to Laframboise's results, which enables double probe measurement of electron temperature and plasma density over a wide range of densities without advance knowledge of the probe radius relative to Debye length. In this investigation, the method was evaluated by comparing plasma properties from three double Langmuir probes of varying electrode diameter. Far-field measurements of a Hall thruster plume were conducted with each probe at two facility background pressures. Plasma characteristics were calculated using the proposed analytical technique, and compared to orbital motion limited and thin-sheath analyses in regions of the plume where these methods are valid. Results revealed equivalent plasma properties from each double probe geometry when using the proposed double probe analysis methodology, indicating the electrode sheath expansion is accounted for. Calculated plasma densities and electron temperatures were consistent with standard analysis techniques. These findings support the proposed double probe analysis method for examination of plasma properties over a wide span of the far-field plume using a fixed Langmuir probe design and a single analysis technique.

I. Introduction

THE growing use of electric propulsion for efficient, in-space maneuverability drives evaluation of electric propulsion plumes in ground-based facilities [1,2,3]. These investigations require measurement over increasing range of plasma properties for laboratory propulsion systems spanning orders magnitude in power, from Watts to over 100kW [1,4]. In addition, properties of the internal thruster plasma and near-field regions are orders of magnitude higher than the extended far-field plume. Langmuir probes, an electrostatic diagnostic developed by Irving Langmuir in 1924 [5], are widely used to examine plasma properties in laboratory investigations and on-orbit environments. Although the electrostatic theory of Langmuir probe operation is straightforward, the implementation and analysis is complicated by several factors, including probe sheath effects that influence electrode(s) current collection and perturbations to the local plasma. These complications necessitate the probes are designed for a specific, narrow range of plasma properties and require analysis techniques that are based on assumptions about the probe sheath interactions with the plasma environment under examination [6].

---

[1] Program Manager, In-Space Propulsion Branch, Aerospace Systems Directorate; daniel.brown@edwards.af.mil, Associate Member AIAA.
[2] Program Manager, In-Space Propulsion Branch, Aerospace Systems Directorate; brian.beal@edwards.af.mil
[3] Research Scientist; joseph.blakely.ctr@edwards.af.mil

PREPRINT – See AIAA 2012 Joint Propulsion Conference Proceedings

Langmuir probes are typically categorized according to geometry and number of electrodes. Probe geometries range from spherical, planar, and cylindrical in nature with one or multiple electrodes. Multiple electrodes typically decrease plasma perturbation due to lower bias voltages at the expense of increased probe size and decreased spatial resolution. The double Langmuir probe configuration, with two electrodes, floats with the plasma and electrodes are swept relative to the floating potential. This has several advantages over the single probe geometry; it eliminates the need for a fixed reference potential, limits biased electrode collected current to the ion saturation current, minimizes local plasma perturbations with a net zero current to the electrode pair, and reduces the electrode voltage sweep. While the triple probe does not require a voltage sweep, the separation between electrodes reduces spatial resolution.

Recent theoretical studies of double Langmuir probe characteristics in low-temperature plasma led to development of a new analysis technique that employs analytical fits to Laframboise's numerical results and circuit analysis to formulate relationships between applied electrode voltage, current collection, and the local plasma properties [7]. These coupled equations account for probe sheath effects, such that it is applicable over a wide range of electron Debye length relative to probe dimensions and spans the expands of measureable plasma properties compared to conventional analyses.

In this paper, the new double Langmuir probe analysis technique [7] is assessed with measurements of a low-power Hall thruster plume using three cylindrical double Langmuir probes of varying scales. This systematic plume mapping encompassed a wide range of plasma properties. Plasma parameters were calculated using the proposed technique and compared to conventional methods, such as orbital motion limited (OML) and thin sheath analysis. Plume mapping was conducted from 20 to 150 thruster diameters downstream at two facility background pressures.

II. Probe Theory

Analyses of Langmuir probe current-voltage (I-V) characteristics are dependent on the length scales of electron Debye length and probe geometry. The size of the plasma sheath surrounding the probe is proportional to the electron Debye length λ_D, as defined in Eq. (1), where T_e is electron temperature, n_e is electron number density, k_B is the Boltzmann constant, and e is the electron charge. The probe is in a collisionless, "thick" sheath regime when the ratio of probe radius r_p to Debye length is $r_p/\lambda_D<3$, often referred to as orbital motion limited (OML). A "thin" sheath analysis is applicable for $r_p/\lambda_D>10$.

$$\lambda_D = \left(\frac{k_B T_e}{e n_e} \right)^{1/2} \tag{1}$$

The transitional regime between the "thick" and "thin" sheath analyses where $3<r_p/\lambda_D<10$ may be analyzed using an iterative approach with Laframboise's comprehensive compilation of collected ion current with respect to electron Debye length for cylindrical or spherical probe geometry [8]. Several analytical fits to Laframboise's results have been proposed, including studies by Steinbruchel, Narasimhan, and Karamcheti [9,10,11] that led to development of analytical parameterization techniques of Laframboise's results that were successfully demonstrated with single Langmuir probe geometries for cold ions ($T_i/T_e<<1$) over a wide span of r_p/λ_D, where T_i is the ion temperature. The parameterization technique has been reformulated for analysis of double Langmuir probes [7], and is valid for all r_P/λ_D if the electron distribution function is Maxwellian. Experimental assessment of the parameterization approach for double probe analysis is the aim of this investigation. An overview of the technique is described below, and additional details are provided elsewhere [7].

A floating double Langmuir probe circuit with ion and electron currents is represented in Fig. 1. The positive sense of ion current and electron current is described by the notation $I_{j,+}$ and $I_{j,e}$, where j indicates electrode 1 or 2. Kirchoff's laws are expressed in Eqs. (2) and (3), where the applied electrode voltage V_j is relative to the local plasma floating potential and the magnitude of the probe current I_p cannot exceed the ion saturation current. Both electrodes are electron repelling (V_1, V_2<0) since the ion saturation current limit is always much smaller than the electron saturation current. One electrode is biased slightly below plasma floating potential and the other slightly above. These characteristics enable formulation of electron currents $I_{j,e}$ in Eq. (4), where A_j is the surface area of a single electrode, e is the magnitude of the electron charge, n_0 is the local number density of the undisturbed plasma, m_e is the electron mass, ξ is the local electron temperature in electron volts (i.e. k_BT_e/e), and $I_{0,e}$ is the thermal electron current to a probe at plasma potential [9]. It is assumed that the undisturbed plasma is both quasineutral and singly-ionized such that the electron and ion densities are equal. Manipulation of Eqs. (2), (3), and (4) results in the fundamental double probe characteristic given by Eq. (5).

$$I_P = I_{1+} - I_{1e} = I_{2e} - I_{2+} \tag{2}$$

$$V_P = V_2 - V_1 \tag{3}$$

$$I_{j,e} = A_j e^{3/2} n_0 \left(\frac{\xi}{2\pi m_e}\right)^{1/2} \exp\left(\frac{V_j}{\xi}\right) = I_{0,e} \exp\left(\frac{V_j}{\xi}\right) \tag{4}$$

$$I_P = I_{1+} \tanh\left(\frac{V_P}{2\xi}\right) + \frac{I_{1+} - I_{2+}}{\exp\left(\frac{V_P}{\xi}\right) + 1} \tag{5}$$

The derivation of Eq. (5) makes no assumptions about the features of the ion current collection mechanism, and thus is applicable for all r_P/λ_D provided that the electron distribution function is Maxwellian, such that Eq. (4) is valid. If the ion saturation current is independent of the applied bias potential (for $I_{1+}=I_{2+}$), then Eq. (5) reduces to the original symmetric double probe formulation of Johnson and Malter [12].

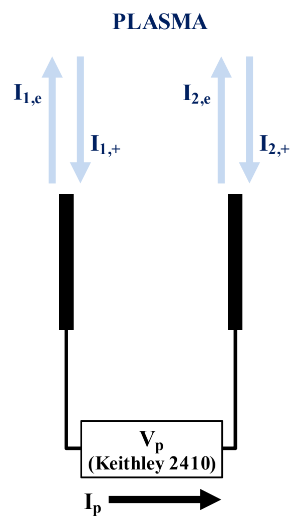


FIG 1. Electrical circuit of double Langmuir probe in plasma, including voltage source meter with ion and electron currents at each electrode.

It has been shown that the ion current collected by a spherical or cylindrical probe can be represented by Eq. (6), where I_0 is the ion current at the sheath edge given by Eq. (7) [9,11]. The fit parameters a and b are functions of r_P/λ_D and are given by the expressions in Table II, which have been reported to produce correlation coefficients greater than 0.997 over the range $3<r_P/\lambda_D<50$ [11]. For the cylindrical probe at values of $r_P/\lambda_D<3$, the true b parameter deviates from the value given by Table I and can be approximated as having a constant value of 0.5 over the range $0< r_P/\lambda_D<3$ [10].

$$I_{j,+} = I_0 a \left(\frac{-V_j}{\xi}\right)^b + I_{End} \tag{6}$$

$$I_0 = e^{3/2} n_0 A \left(\frac{\xi}{2\pi m_i}\right)^{1/2} \tag{7}$$

Table II. The fit parameters *a* and *b* for $3<r_P/\lambda_D<50$ (from Ref. 11).

Probe geometry	a	B
cylindrical	$1.18-0.00080(r_P/\lambda_D)^{1.35}$	$0.0684+(0.722+0.928 \times r_p/\lambda_D)^{-0.729}$
spherical	$1.58+(-0.056+0.816 \times r_P/\lambda_D)^{-0.744}$	$-0.933+(0.0148+0.119 \times r_P/\lambda_D)^{-0.125}$

The expression above for the collected ion current can be inserted into Eq. (5) to yield the final double probe current characteristic, which is given by Eqn. (8). To make use of this expression in deducing plasma parameters from experimental data, one must first relate the potential of electrode 1, V_1, to a directly measurable quantity such as V_P. This is accomplished by noting that the probe as a whole floats such that no net current is drawn from the plasma, as shown by Eq. (9). This equation can be solved implicitly to yield V_1 as a function of V_P for a given ion species, electron temperature, and predetermined values of the fit parameters *a* and *b*.

$$\frac{I_P}{I_0} = a\left(\frac{-V_1}{\xi}\right)^b \tanh\left(\frac{V_P}{2\xi}\right) + \frac{a\left(\frac{-V_1}{\xi}\right)^b - a\left(\frac{-(V_1+V_P)}{\xi}\right)^b}{\exp\left(\frac{V_P}{\xi}\right)+1} \tag{8}$$

$$I_{1+} + I_{2+} - I_{1e} - I_{2e} = a\left[\left(\frac{-V_1}{\xi}\right)^b + \left(\frac{-(V_1+V_P)}{\xi}\right)^b\right] - \left(\frac{m_i}{m_e}\right)^{1/2} \exp\left(\frac{V_1}{\xi}\right)\left[1+\exp\left(\frac{V_P}{\xi}\right)\right] = 0 \tag{9}$$

III. Experimental Apparatus

A. Vacuum Facilities and Low Power Hall Effect Thruster

The investigation was conducted at the Air Force Research Laboratory (AFRL) in the Space Environmental Facility (SPEF), a stainless steel, spherical vacuum chamber 9.1-m in diameter. SPEF utilizes six 48” diffusion pumps with liquid nitrogen cooled cold traps. The facility has demonstrated xenon pumping speeds greater than 300,000 l/s and base pressure of 1×10^{-6} torr-xenon. Two MKS Instruments cold cathode gauges (CCG) were located on the walls as shown in Fig. 2, and background pressure was varied by changing the number of operating diffusion pumps.

A Velmex motion control system consisting of three-axis translation and a rotation stage, illustrated in Fig. 3, was used to position the plasma diagnostic array through-out the Hall thruster plume. The translation path and measurement positions in Fig. 3 show the measurement radius from 0.24 m to 3.7 m in 2 degree increments. Following the coordinate system shown in Fig. 3, this system enables probe measurements over a 5.79-m X-axis, 0.51-m Y-axis, and 4.57-m Z-axis range with 180° of rotation. The probes were mounted in parallel on a common diagnostic array, spaced approximately 5 inches apart. At each measurement location, the diagnostic array was rotated for each probe such that the probe was pointed toward the thruster center. Although this leads to minor differences in position between the three probes at a measurement location, the data is interpolated in Igor Pro using Delaunay triangulation. Probe positions were accurate to within 2.5 cm throughout each plume scan.

The ion source for these experiments was a low-power laboratory Hall thruster. Prior to Langmuir probe data collection, the thruster was fired for over one hour after initial start-up. Thruster telemetry was monitored during probe sweeps, and exhibited negligible deviation from steady-state operation.

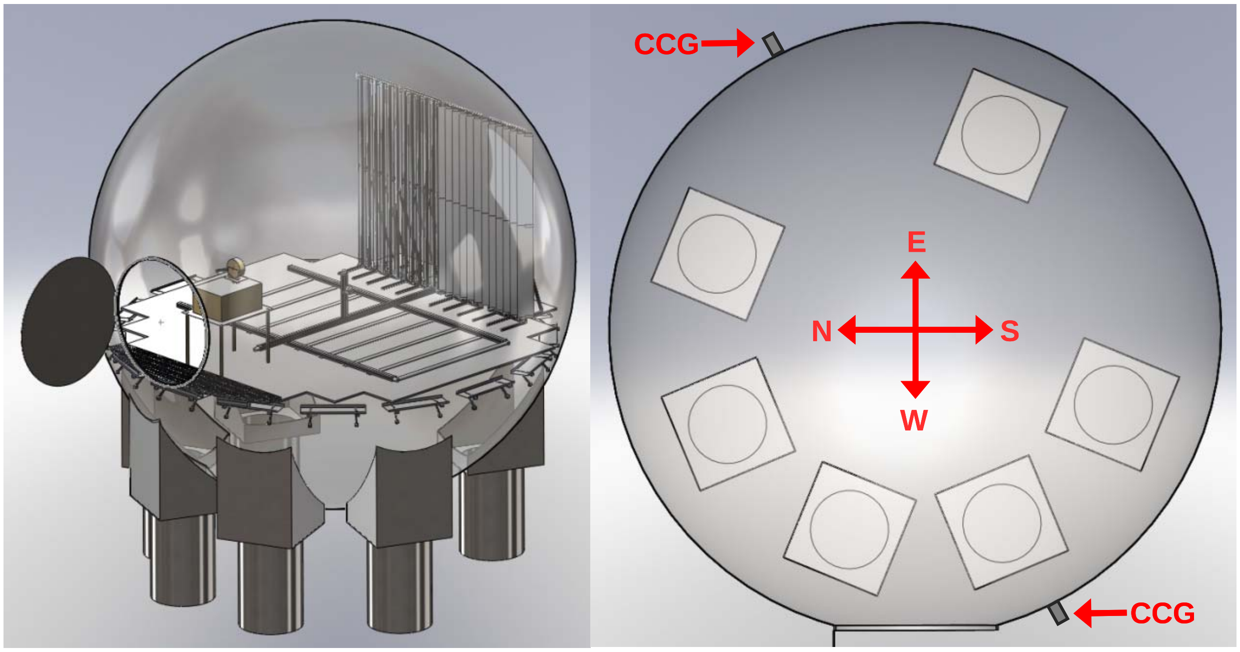


FIG 2. Illustration of SPEF with experimental setup within (left) and top-down view of diffusion pump and CCG locations (right).

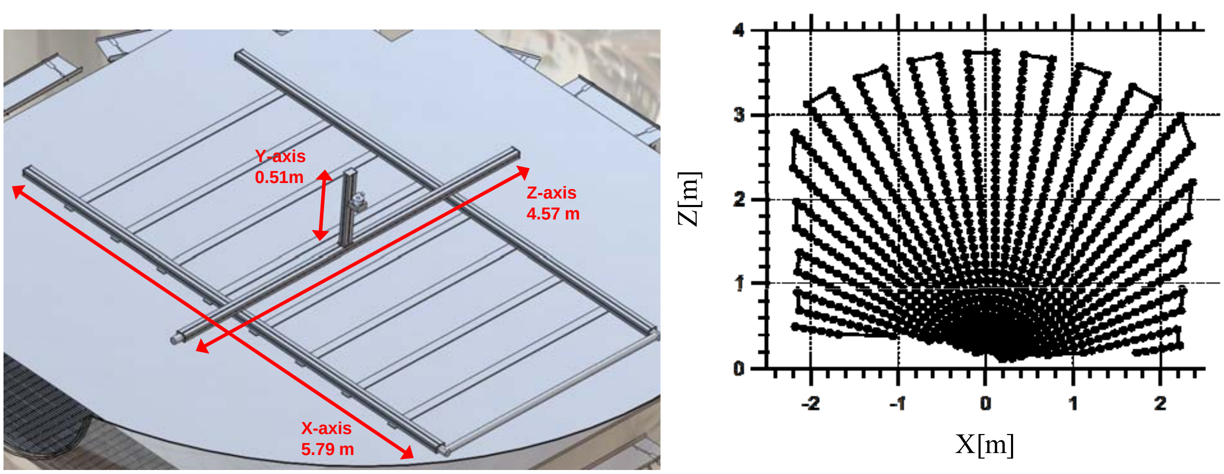


FIG 3. Illustration of SPEF motion control stages and axes (left). Probe array translation path and measurement locations (right).

B. Double Langmuir Probes

The three cylindrical, double Langmuir probes used in this investigation were designed for OML analysis, and scaled to enable far-field measurement over a wide range of number density spanning four orders of magnitude from 10^{16} m^{-3} in the central plume to 10^{13} m^{-3} in the outer periphery. Probe dimensions are listed in Table 1 and the probe array is shown in Fig. 4. Using a single analysis method such as OML required three or more double probe geometries. Likewise, using any single probe with multiple analysis methods, including OML ($r_P/\lambda_D<3$) and thin-sheath ($r_P/\lambda_D>10$), would limit the regions where accurate measurements can be acquired due to low signal, poor spatial resolution, or blending of analysis methods where $3<r_P/\lambda_D<10$.

Cylindrical probe electrodes were tungsten rod and extended from the diagnostics array housing through an alumina sleeve. The rotation stage oriented each probe toward the thrust axis at the Hall thruster exit plane where (X, Z) = (0, 0), such that plasma flow was aligned with the probe electrode axis. Past studies have shown the double probe plasma I-V characteristic may be analyzed as a stationary plasma in this orientation, provided the electrode length is much greater than the diameter [13]. In this study, all electrode length to diameter ratios exceeded 10:1, and are sufficient to meet this criteria. A Keithley 2410 sourcemeter was swept from -15 V to +15 V using the circuit schematic illustrated in Fig. 1.

Table 1 Double Langmuir probe dimensions

Double Langmuir Probe	Electrode Diameter [mm]	Electrode Length [cm]	Electrode Spacing [cm]
Probe 1	**0.254**	**5.08**	**4.45**
Probe 2	**3.175**	**12.2**	**5.72**
Probe 3	**9.525**	**19.70**	**5.72**

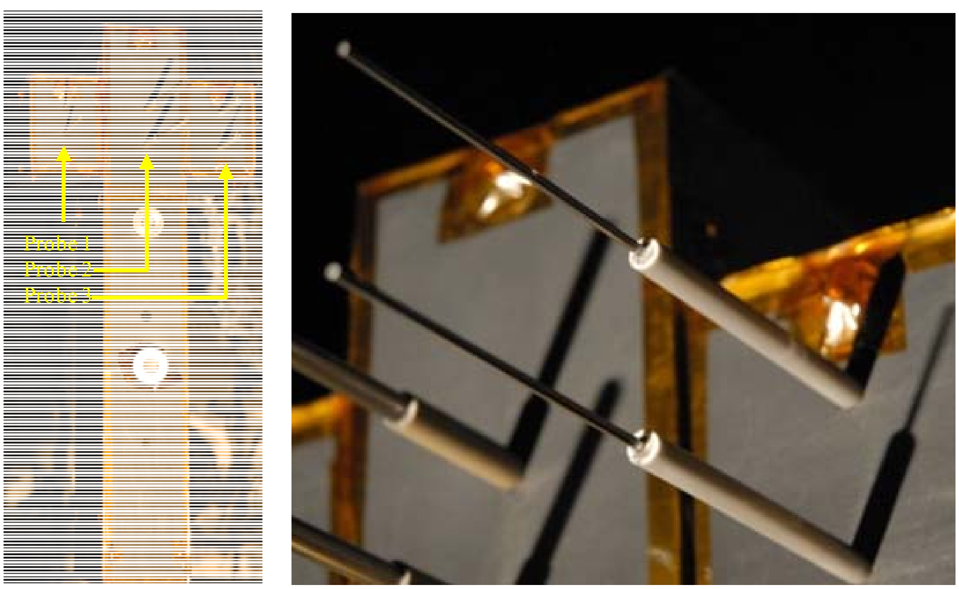


FIG 4. Photographs of the diagnostics array (left) with close-up double Langmuir probe 2 (right).

IV. Results and Discussion

Double Langmuir probe results were normalized to a consistent value and plotted with respect to thruster diameter, ranging 150 diameters downstream and to 80 diameters on the periphery. Probe 1 was designed for the highest density regions, and exhibited minimal signal to noise beyond approximately 40 thruster diameters. Probe 2 was designed to span the entire range of plasma properties throughout the plume with OML analysis. Probe 3 was designed for the low density regions on the plume periphery, and due to its size suffered from poor spatial resolution within 20 thruster diameters.

Number density calculated using the analysis technique described in Ref. 7 is compared to OML in Fig. 5 for Probes 2 and 3. This qualitative assessment indicates the number densities calculated with Ref. 7 are consistent between Fig. 5a and Fig. 5c, corresponding to Probe 3 and 2 respectively. For both probes, number density in the central plume in Figs 5a and 5c calculated with Ref. 7 extend further downstream compared to OML analysis in Figs. 5b and 5d. Comparison the central plume in Figs. 5c and 5d indicates Probe 2 has better agreement between Ref. 7 and OML, whereas Figs. 5a and 5b show Probe 3 results in similar features between Ref. 7 and OML on the periphery. These trends in OML analysis are consistent with expected results due to the poor spatial resolution of Probe 3 nearest the thruster and the reduced signal of Probe 2 on the far wings of the plume. The agreement between Probe 2 and 3 using the analysis of Ref. 7 indicates it accounts for sheath physics across a range of r_P/λ_D, and is suitable for the transitional regime where OML is not valid, when r_P/λ_D>3.

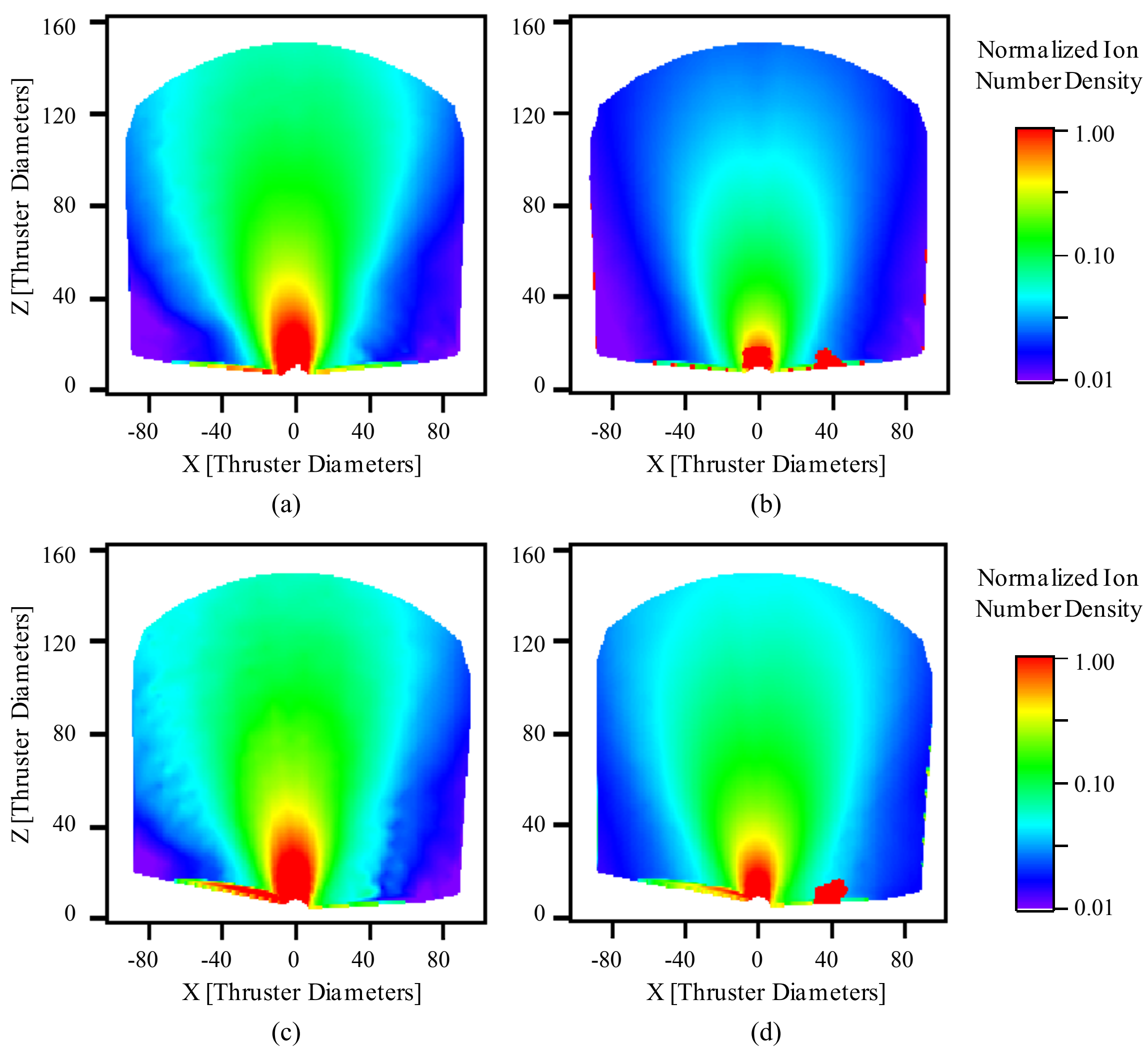


FIG 5. Comparison of normalized number density of double Langmuir Probe 3 using analysis of (a) Ref. 7 and (b) OML, and of Probe 2 using analysis of (c) Ref. 7and (d) OML at low background pressure.

In Fig. 6, number density calculated using the analysis technique described in Ref. 7 is compared to OML for Probes 1 and 2, where the signal to noise of Probe 1 is adequate for analysis of plasma properties. This qualitative assessment indicates the number densities calculated with Ref. 7 are consistent between Fig. 6a and Fig. 6c, corresponding to Probe 2 and 1 respectively. Comparison the central plume in Figs. 6c and 6d indicates Probe 1 has better agreement between Ref. 7 and OML, whereas Figs. 6a and 6b show Probe 2 results in conflicting features between Ref. 7 and OML in the highest density region nearest the thruster. These trends indicate the Probe 2 OML analysis in Fig. 6b are influenced by reduced spatial resolution of Probe 2 nearest the thruster and that the probe is no longer in the OML analysis regime. The agreement between Probe 1 and 2 using the analysis of Ref. 7 indicates it accounts for sheath physics across a range of r_P/λ_D, and is suitable for the transitional regime where OML is not valid, when $r_P/\lambda_D>3$.

Centerline number density from the three double probe configurations are calculated with thin sheath, parametric analysis in Ref. 7, and OML in Figs. 7 to 9. Trends indicate the analysis of Ref. 7 is in agreement with thin sheath analysis out to approximately 25 to 45 thruster diameters, and in agreement with OML analysis beyond approximately 50 diameters. This suggests the analysis of Ref. 7 is bridging the plasma properties from OML analysis to thin sheath, and is advantageous for determination of plasma properties across wide regions of the Hall thruster plume. Based on past simulations of the plume, the location between approximately 30 to 50 thruster diameters downstream of the exit plane corresponds to the transition region where $3<r_P/\lambda_D<10$.

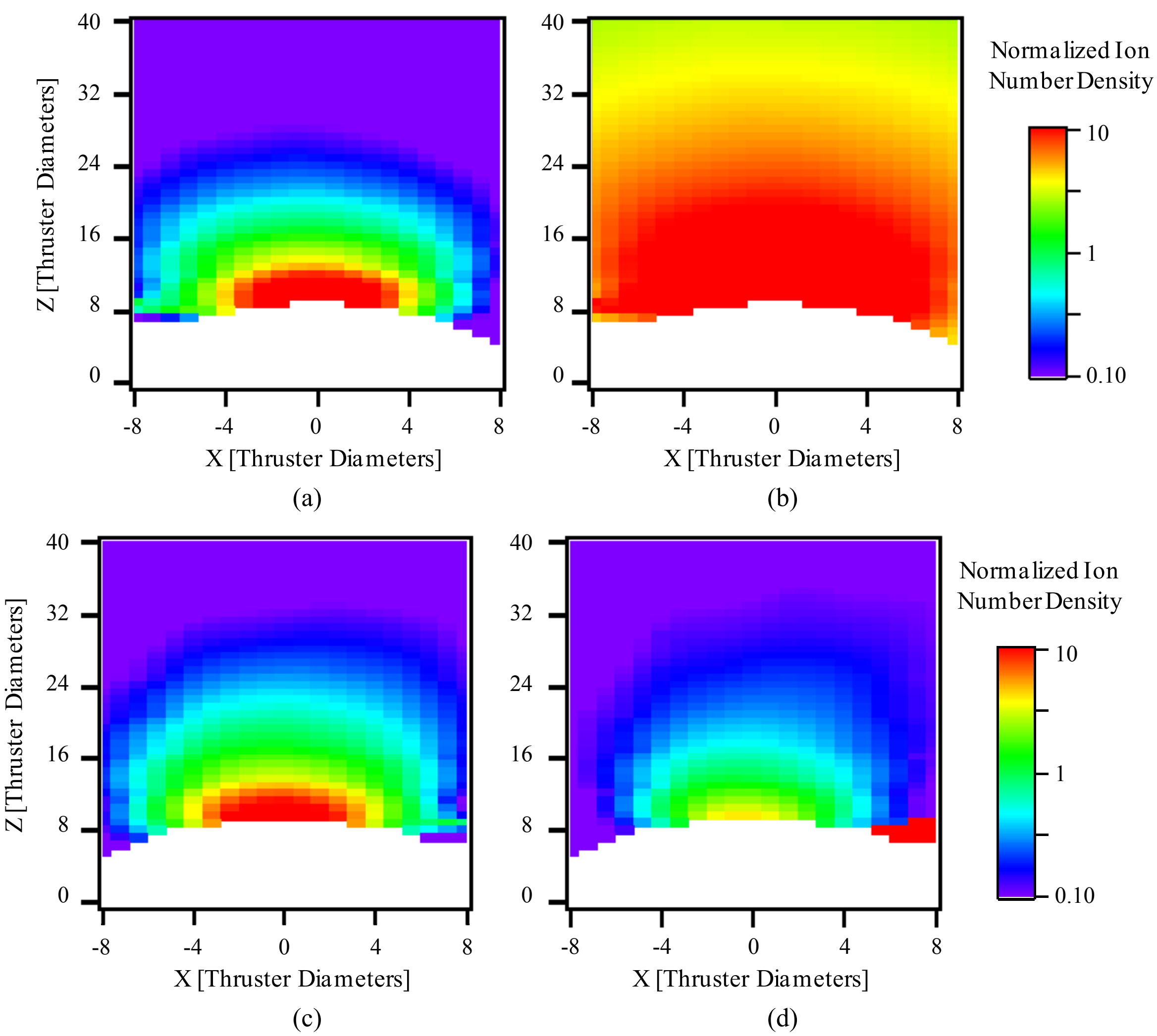


FIG 6. Comparison of normalized ion number density of double Langmuir Probe 2 using analysis of (a) Ref. 7 and (b) OML, and of Probe 1 using analysis of (c) Ref. 7 and (d) OML at low background pressure.

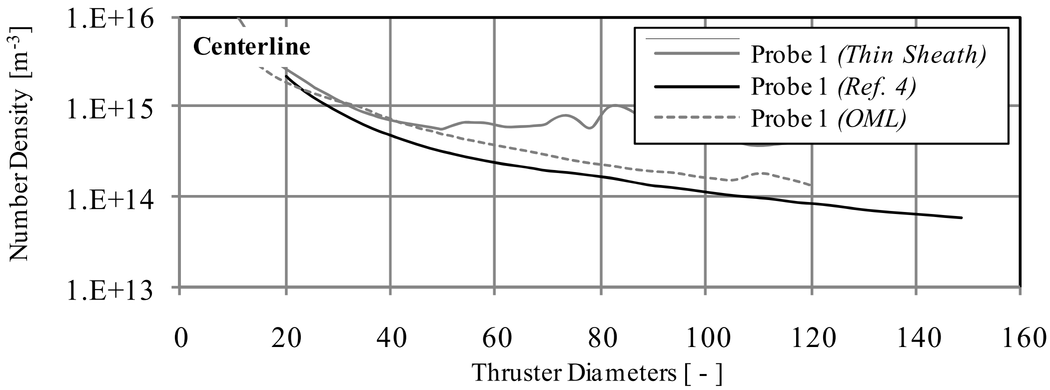


FIG 7. Comparison of normalized ion number density of double Langmuir Probe 1 using thin sheath, Ref. 7, and OML at low background pressure.

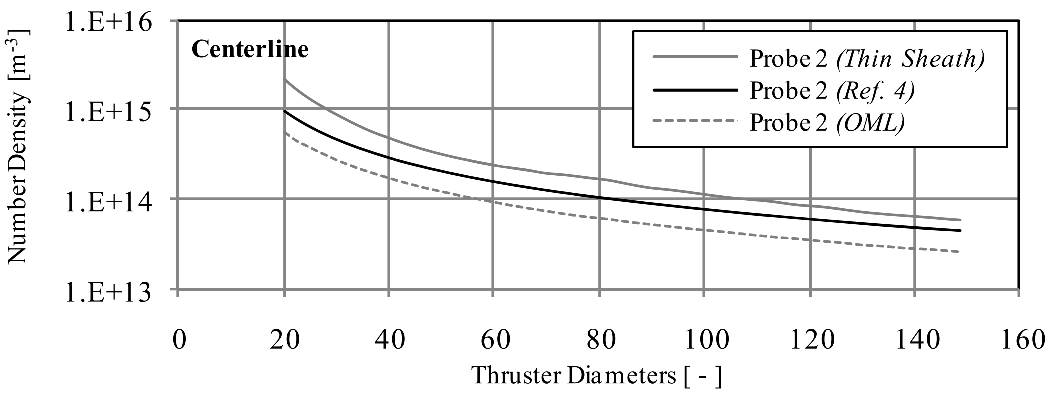


FIG 8. Comparison of normalized ion number density of double Langmuir Probe 2 using thin sheath, Ref. 7, and OML at low background pressure.

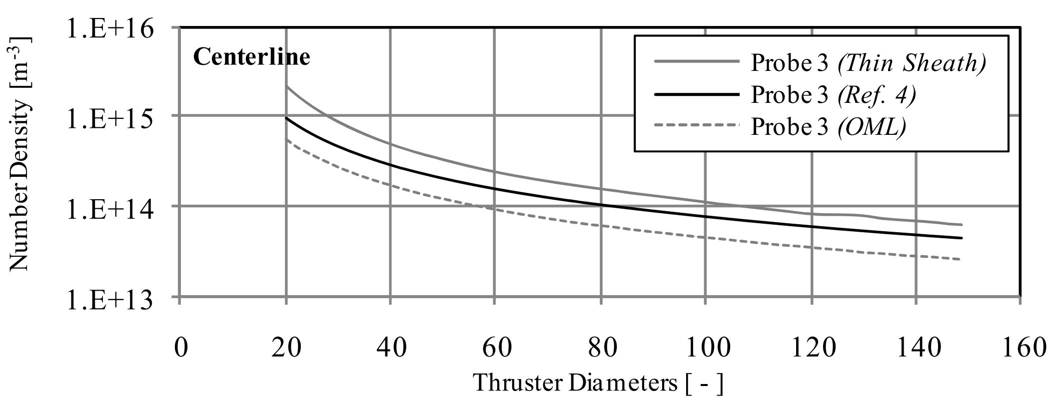


FIG 9. Comparison of normalized ion number density of double Langmuir Probe 3 using thin sheath, Ref. 7, and OML at low background pressure.

The centerline number densities all three probes calculated using Ref. 7 in Figs. 7 to 9 are shown in Fig. 10. This shows good centerline agreement between all three probes to 40 thruster diameters downstream, and highlights issues in Probe 1 due to low signal to noise. Consistent values between Probe 2 and Probe 3 are further indication that the analysis in Ref. 7 accounts for probe sheath effects. Fig. 11 shows the electron temperature on thruster centerline for all three probes corresponding to data in Fig. 10. While there is considerable uncertainty in electron temperature calculations, it shows consistent agreement between Probes 2 and 3 from 20 to 150 thruster diameters, is consistent with past studies using this low-power Hall thruster.

The agreement between Probes 2 and 3 on thruster centerline in Fig. 10 are further evaluated in Figs. 12 to 17 for low and high facility background pressures on centerline, θ=30°, and θ=60° from the thruster centerline axis. Comparisons between Ref. 7 and OML reveal significantly better agreement between parameters calculated with Ref. 7. The exception is for Probe 3 within 40 thruster diameters when θ=30°, which is attributed to poor spatial resolution. Beyond 40 thruster diameters, calculations using Ref. 7 and OML are in good agreement for θ=30° and θ=60° for both low and high pressure cases.

Comparisons of calculated plasma properties using OML, thin sheath, and Ref. 7 do not necessarily reduce measurement uncertainty, but provide confidence in measurements with a fixed probe design using a single analysis technique in Ref. 7. The wide range of plasma properties over this expansive range of the far-field Hall thruster plume is highly advantageous for investigations of a Hall thruster or ion thruster plume, due to the increased range of plasma properties that can be measured, the reduced complexity of analysis, and the flexibility to study a wide range of properties in a time-varying plasma with variation in sheath characteristics.

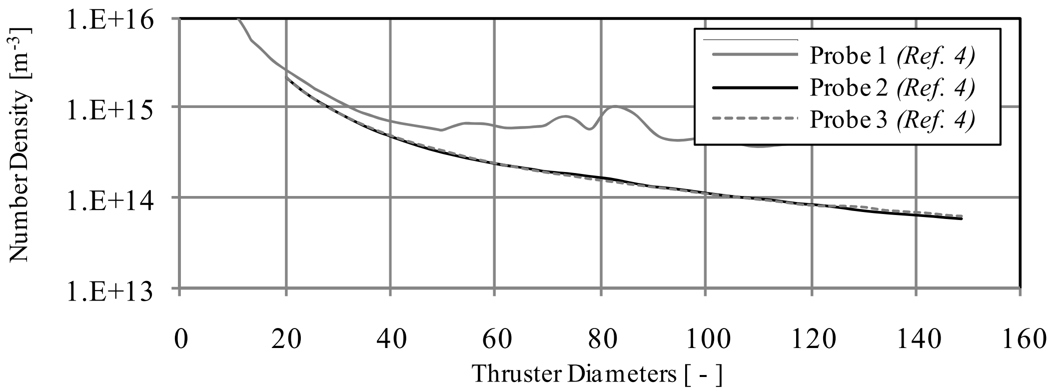


FIG 10. Comparison of normalized ion number density of double Langmuir Probes 1, 2, and 3 at θ=0° using analysis of Ref. 7 at low background pressure.

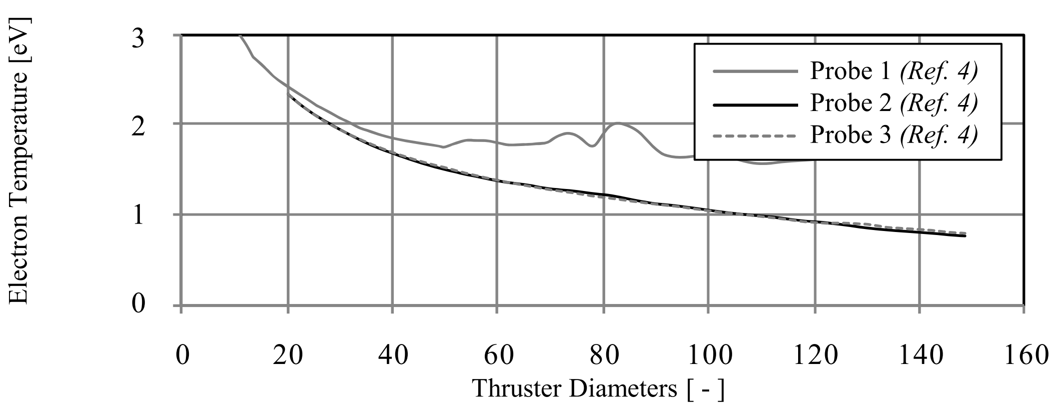


FIG 11. Normalized electron temperature of double Langmuir Probes 1, 2, and 3 at θ=0° using analysis of Ref. 7 at low background pressure.

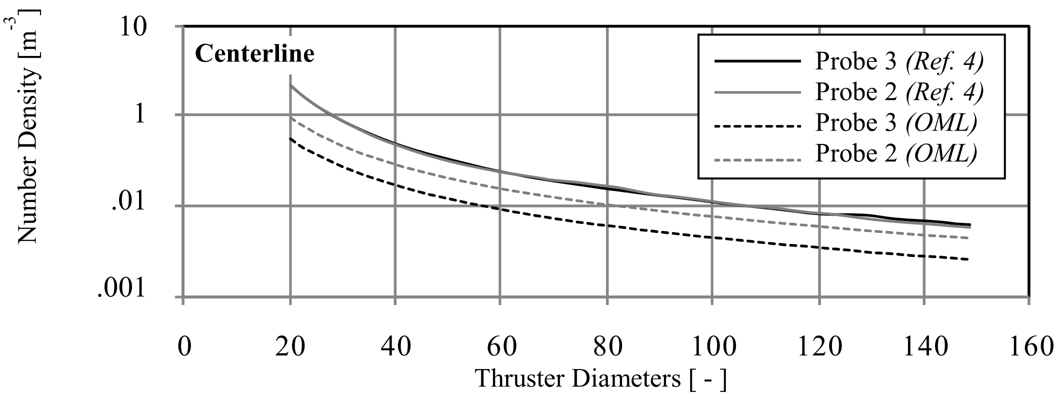


FIG 12. Normalized ion number density of double Langmuir Probes 2 and 3 at θ=0° using analysis of Ref. 7 and OML at low background pressure.

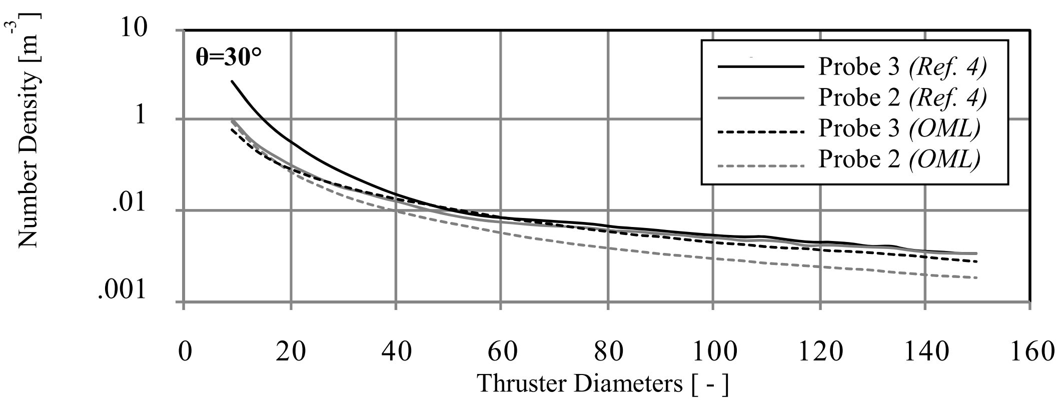


FIG 13. Normalized ion number density of double Langmuir Probes 2 and 3 at θ=30° using analysis of Ref. 7 and OML at low background pressure.

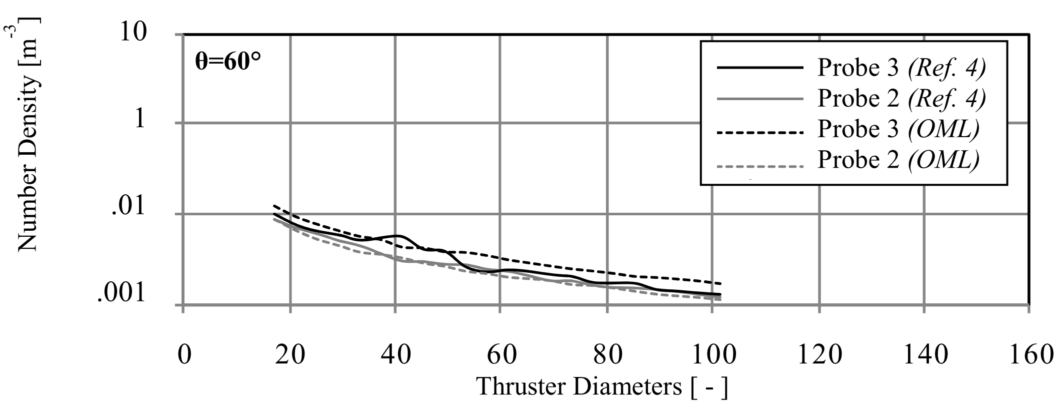


FIG 14. Normalized ion number density of double Langmuir Probes 2 and 3 at θ=60° using analysis of Ref. 7 and OML at low background pressure.

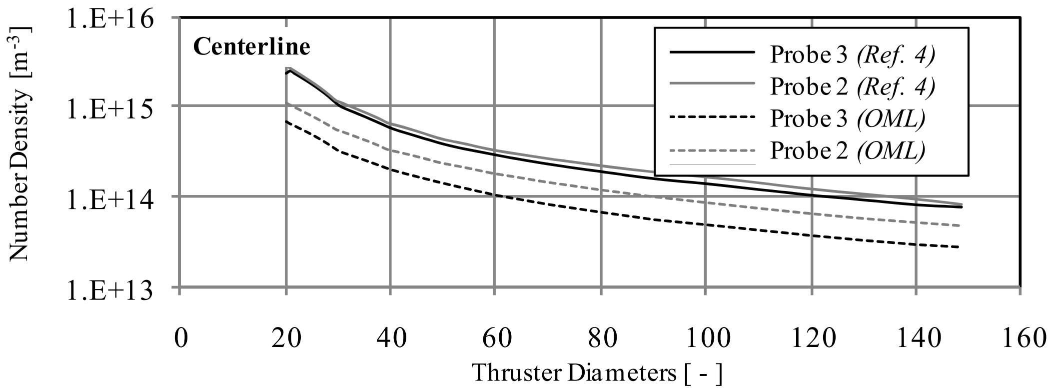


FIG 15. Normalized ion number density of double Langmuir Probes 2 and 3 at θ=0° using analysis of Ref. 7 and OML at high background pressure.

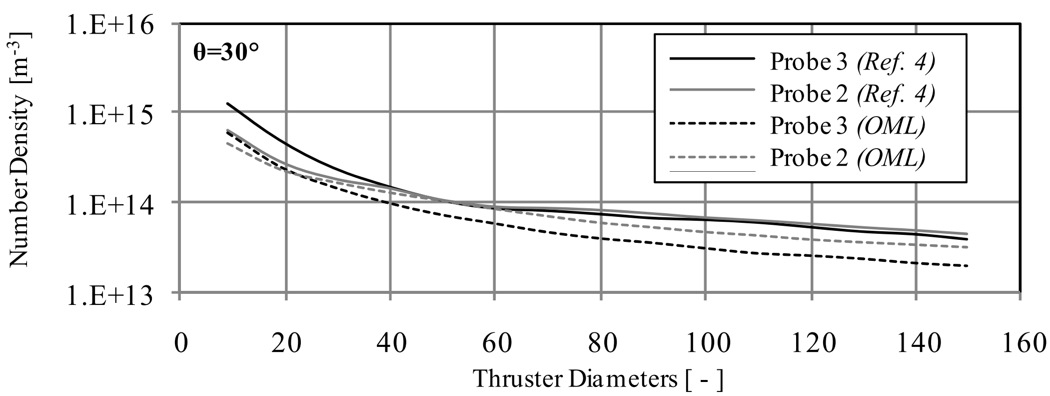


FIG 16. Normalized ion number density of double Langmuir Probes 2 and 3 at θ=30° using analysis of Ref. 7 and OML at high background pressure.

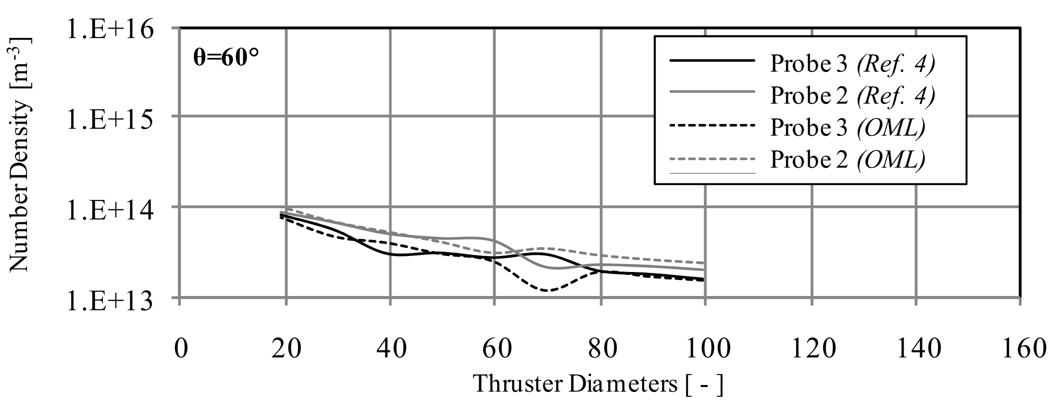


FIG 17. Normalized ion number density of double Langmuir Probes 2 and 3 at θ=60° using analysis of Ref. 7 and OML at high background pressure.

V. Summary and Conclusions

A new double Langmuir probe analysis technique based on fits to Laframboise's data, and self-consistently accounts for probe sheath expansion in the local plasma. The technique extends past parametric fits of single Langmuir probe data to the double probe configuration in a low-temperature plasma. The methods enable double probe measurement of electron temperature and plasma density over a wide range of densities without advance knowledge of the probe radius relative to Debye length. This has implications for laboratory experiments and on-orbit measurements.

The technique was evaluated with plume measurements of a low-power Hall thruster using three double Langmuir probe designs. Plasma properties calculated with the new analysis technique were consistent with OML and thin sheath analysis, and demonstrated agreement between the three probes throughout the plume. This was successfully verified at two facility background pressures and number densities spanning four orders of magnitude out to 150 thruster diameters from the thruster exit plane. The study suggests this double Langmuir probe technique is well-suited for low-temperature plasmas in the far-field electric propulsion plume, and has several key advantages over traditional analysis techniques, including: the ability to measure a wide range of plasma density with a fixed probe design and a single analysis technique, reduced complexity in data analysis over a wide range of r_p/λ_D, and the flexibility to study a wide range of properties in a time-varying plasma with variation in sheath characteristics.

References

[1] Busek Press Release, "First US Hall Thruster Operational in Space from TacSat-2," January 4, 2007.

[2] Hofer, R. R., Randolph, T. M., Oh, D. Y., Snyder, J. S., and De Grys, K. H., "Evaluation of a 4.5 kW Commercial Hall Thruster System for NASA Science Missions," AIAA Paper 2006-4469, July 2006.

[3] De Grys, K. H., Mathers, A., Welander, B., and Khayms, V., "Demonstration of 10,400 Hours of Operation on 4.5 kW Qualification Model Hall Thruster," AIAA Paper 2010-6698, July 2010.

[4] Florenz, R., Gallimore, A. D., Peterson, P. Y., "Development Status of a 100-kW Class Laboratory Nested Channel Hall Thruster," IEPC Paper 2011-246, September, 2011.

[5] Mott-Smith, H. M., Langmuir, I., "Langmuir Probe Theory," *Physical Review*, Vol. 28, pp. 727, 1926.

[6] Chen, F. F., "Langmuir Probe Analysis for High Density Plasmas," *Physics of Plasmas*, Vol. 8, No. 6, pp. 3029-3041, June 2001.

[7] Beal, B. E., Johnson, L., Brown, D. L., Blakely, J. M., Bromaghim, D., "Improved Analysis Techniques for Cylindrical and Spherical Double Probes," Rev. Sci. Instrum., (accepted May 2012).

[8] Laframboise, J. G., "Theory of Spherical and Cylindrical Langmuir Probes in a Collionless, Maxwellian Plasma at Rest," UTIAS Report No. 100, June, 1966.

[9] A. Karamcheti and Ch. Steinbruchel, J. Vac. Sci. Technol. A, **17**, 3051 (1999).

[10] Ch. Steinbruchel, J. Vac. Sci. Technol. A, **8**, 1663 (1990).

[11] G. Narasimhan and Ch. Steinbruchel, J. Vac. Sci. Technol. A, **19**, 376 (2001) [or , G. and Steinbruchel, Ch., "Analysis of Langmuir probe Data: Analytical Parameterization, and the Importance of the End Effect," J. Vac. Sci. Technol. A 19(1), Jan/Feb 2001].

[12] E. O. Johnson and L. Malter, Physical Review, **80**, 58 (1950).

[13] P.M. Chung, L. Talbot, and K.J. Touryan, AIAA Journal, **12**, 2 (1974).

Experimental Assessment of Double Langmuir Probe Analysis Techniques in a Hall Thruster Plume

2012 AIAA Joint Propulsion Conference

Daniel L. Brown
Brian E. Beal
Joseph M. Blakely

Spacecraft Branch (RZSS)
Air Force Research Laboratory
Edwards AFB, CA

Integrity ★ Service ★ Excellence

Overview

Background and Motivation

Probe Theory

Experimental overview and scope

Apparatus and Facilities

Plume Data

Summary and Conclusions

Background and Motivation

Background

- Double probe theory based on theoretical analysis at AFRL[1]
- Valid for low temperature plasma
- Based on analytical fits to Laframboise's results, extended to double probe geometry

Advantages over conventional techniques

- Self-Consistent → *Accounts for sheath expansion*
- Simple → *Enables single analysis method with fixed probe design*
- Enabling → *Expands measurement range for transient plasmas*

Apply to low-temperature plasmas with a wide range of densities without a priori tailoring of probe dimensions to the expected electron Debye length

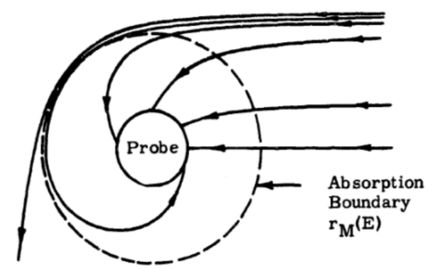
[1] Beal, B. E., Johnson, L., Brown, D. L., Blakely, J. M., Bromaghim, D., "Improved Analysis Techniques for Cylindrical and Spherical Double Probes," *(Accepted by Rev. Sci. Instrum. 2012).*

Probe Theory (1/3)

Standard Langmuir Probe Analysis Techniques

Orbital Motion Limited (OML)

- Valid for small diameter probes, low density plasma
- Plasma sheath infinitely large compared to the probe dimensions *($r_p/\lambda_D<3$)*
- *S*heath does not limit the penetration of the electric field into the bulk plasma
- Probe collects all ions whose momentum relative to the probe surface is insufficient to escape the electric field



* J.G. Laframboise, *Theory of Spherical and Cylindrical Langmuir Probes in a Collisionless, Maxwellian Plasma at Rest,* (University of Toronto Institute for Aerospace Studies, Toronto, 1966), Report No. 100.

Thin Sheath Analysis

- Valid for large diameter probes, high density plasma
- Plasma sheath small relative to the probe dimensions *($r_p/\lambda_D>10$)*
- Probe collects all ions that enter the sheath

Electron Debye Length

$$\lambda_D = \left(\frac{k_B T_e}{e n_e} \right)^{1/2}$$

Interpretation requires knowledge of the relation between the ion current collected by a biased electrode and the local plasma parameters

Probe Theory (2/3)

Standard Langmuir Probe Analysis Techniques

Laframboise's Results for Collisionless Plasma[2]

- Several analytical fits developed, valid over a limited range of r_p/λ_D
- Iterative approach to determine properties
- Requires prior knowledge/assumptions about local plasma
- Multiple regimes and transition complicates analysis
- Typically achieve ~50% uncertainty
- Analytical parameterization for single electrode probes that is applicable over a wide range of r_p/λ_D for cold ions (T_i/T_e<<1)[3,4,5]
- Encompasses wide range of plasma properties *(OML, thin sheath, and transition)*

Extend Parameterization to Double Probe Geometry

[Ref 1]

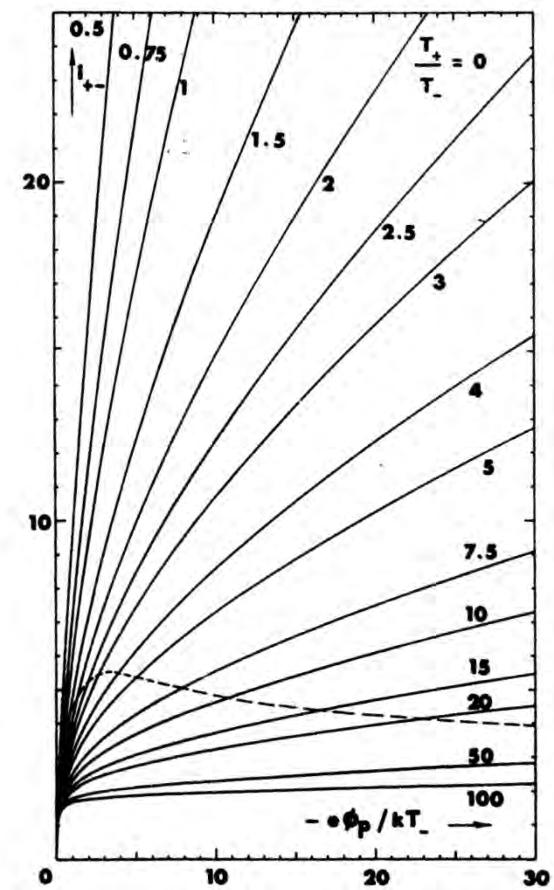


FIGURE 21 ION CURRENT i_{+-} VS PROBE POTENTIAL FOR VARIOUS RATIOS OF PROBE RADIUS TO ELECTRON DEBYE LENGTH; ION-ATTRACTING SPHERICAL PROBE; $T_+/T_- = 0$; ELECTRONS REFLECTED BY PROBE SURFACE; OBTAINED FROM NUMERICAL SOLUTION OF THE ALLEN, BOYD, AND REYNOLDS EQUATION. DOTTED CURVE SHOWS TRAPPED-ORBIT BOUNDARY.

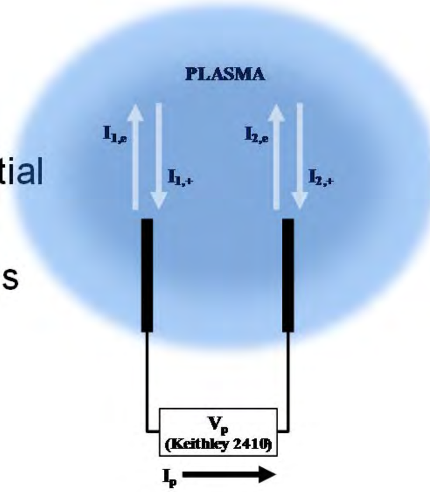
[2] J.G. Laframboise, *Theory of Spherical and Cylindrical Langmuir Probes in a Collisionless, Maxwellian Plasma at Rest,* (University of Toronto Institute for Aerospace Studies, Toronto, 1966), Report No. 100.
[3] A. Karamcheti and Ch. Steinbruchel, J. Vac. Sci. Technol. A, **17**, 3051 (1999).
[4] Ch. Steinbruchel, J. Vac. Sci. Technol. A, **8**, 1663 (1990).
[5] G. Narasimhan and Ch. Steinbruchel, J. Vac. Sci. Technol. A, **19**, 376 (2001).

Probe Theory (3/3)

Improved Double Probe Technique

Extend Parameterization Technique to Double Probe Geometry[1]

- Self-consistent manner that does not require knowledge of the local plasma potential *(unlike the single probe)*
- Find electron temperature and plasma density over wide range of r_p/λ_D for cold ions
- Double probe circuit with Kirchoff's Laws
- Accounts for finite, but non-negligible extend of plasma sheath in transition region



Kirchoff's Laws and Double Probe Theory

$$V_P = V_2 - V_1$$

$$I_P = I_{1+} - I_{1e} = I_{2e} - I_{2+}$$

$$I_{j,e} = A_j e^{3/2} n_0 \left(\frac{\xi}{2\pi m_e}\right)^{1/2} \exp\left(\frac{V_j}{\xi}\right) = I_{0,e} \exp\left(\frac{V_j}{\xi}\right)$$

$$I_P = I_{1+} \tanh\left(\frac{V_P}{2\xi}\right) + \frac{I_{1+} - I_{2+}}{\exp\left(\frac{V_P}{\xi}\right) + 1}$$

Valid regardless of r_P/λ_D so long as the electron distribution function is Maxwellian

Fitting Parameters for Analytical Parameterization[3,4,5]

$$I_0 = e^{3/2} n_0 A \left(\frac{\xi}{2\pi m_i}\right)^{1/2}$$

$$I_{j,+} = I_0 a \left(\frac{-V_j}{\xi}\right)^b + I_{End}$$

For $3 < r_P/\lambda_D < 50$

$a = 1.18 - 0.00080 (r_P/\lambda_D)^{1.35}$

$b = 0.0684 + (0.722 + 0.928 \times r_p/\lambda_D)^{-0.729}$

else $b = 0$ for $r_P/\lambda_D < 3$

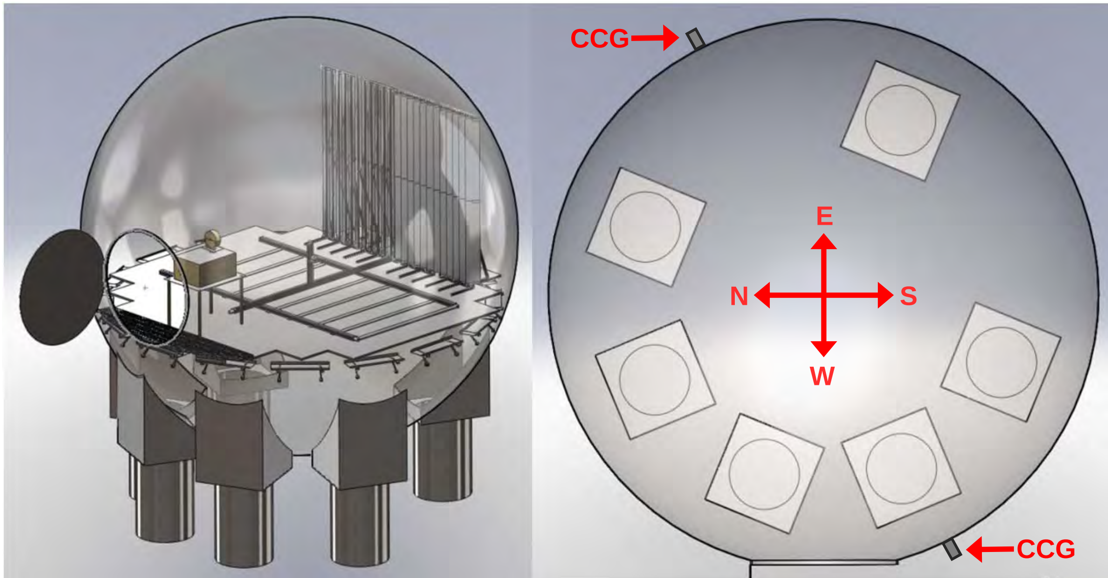
$$\frac{I_P}{I_0} = a\left(\frac{-V_1}{\xi}\right)^b \tanh\left(\frac{V_P}{2\xi}\right) + \frac{a\left(\frac{-V_1}{\xi}\right)^b - a\left(\frac{-(V_1+V_P)}{\xi}\right)^b}{\exp\left(\frac{V_P}{\xi}\right)+1}$$

$$I_{1+} + I_{2+} - I_{1e} - I_{2e} = a\left[\left(\frac{-V_1}{\xi}\right)^b + \left(\frac{-(V_1+V_P)}{\xi}\right)^b\right] - \left(\frac{m_i}{m_e}\right)^{1/2} \exp\left(\frac{V_1}{\xi}\right)\left[1+\exp\left(\frac{V_P}{\xi}\right)\right] = 0$$

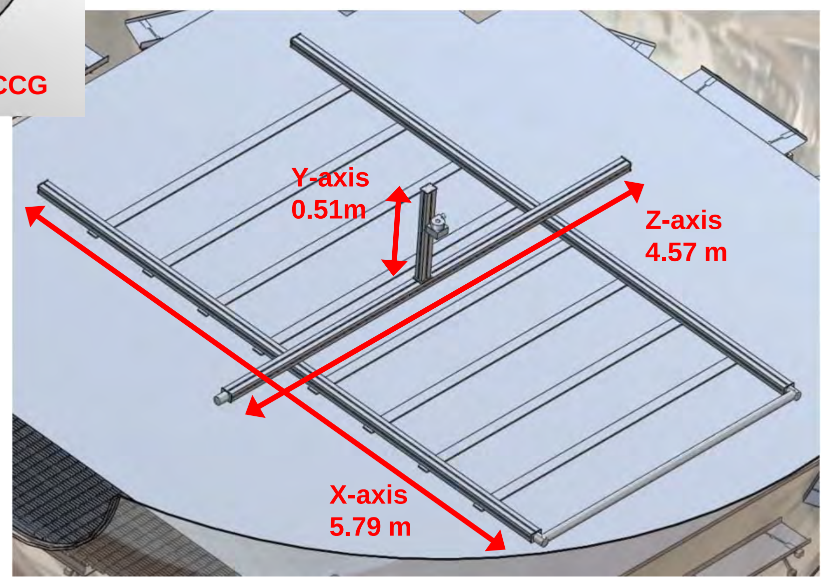
Experimental Overview (1/2)

Facilities and Plasma Environment

- SPEF vacuum chamber
  - 9.1-m diameter stainless steel sphere
  - Six 48” diffusion pumps, greater than 300,000 L/s on Xe
  - Velmex Motion control system w/ 3-axis translation, 180 degree rotation



- Low power Hall thruster ion source
- Two background pressures (vary # DPs)
- Plasma conditions expected to range from OML to thin sheath based on past measurements with this thruster

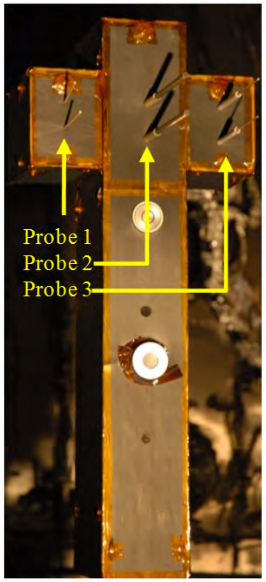


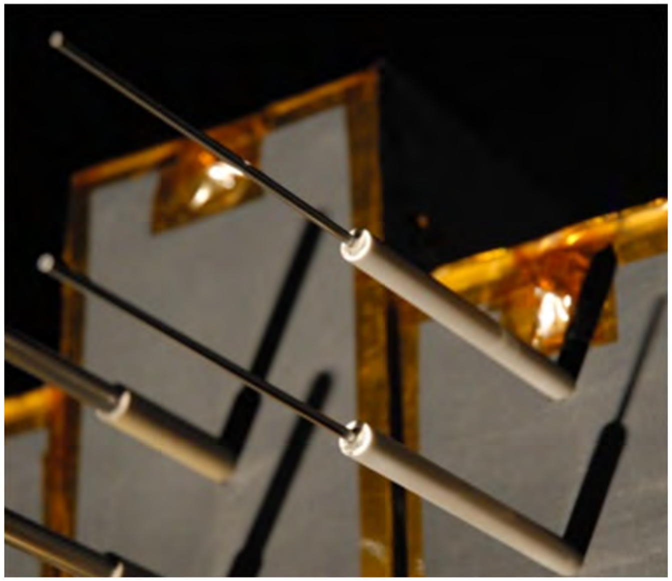
Experimental Overview (2/2)

Diagnostics

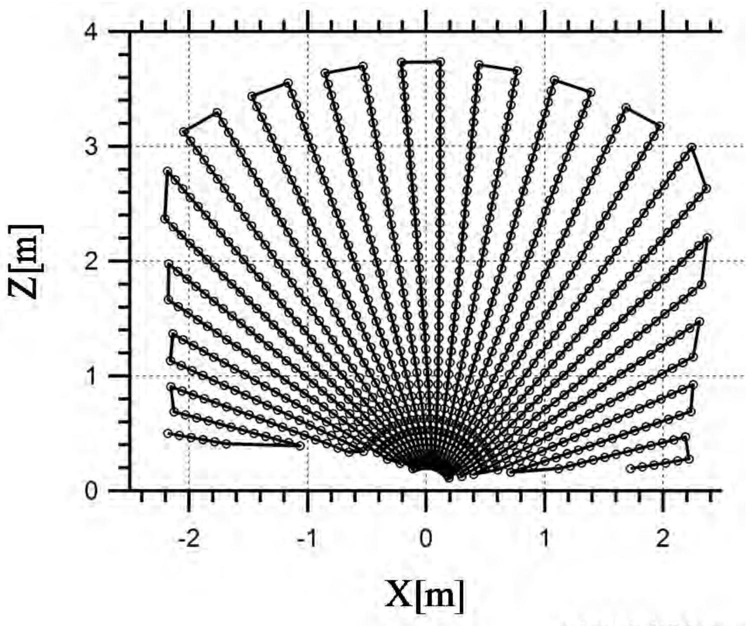
Langmuir Probe Design

- 3 Probes scaled to measure for measurement throughout plume
- Evaluate w/ new technique to compare with thin sheath and OML (where valid)
- Tungsten rod electrodes, alumina tube
- Keithley 2410 sourcemeter used to sweep electrodes from -15 V to +15 V
- Measure 150 thruster diameters downstream (+/- 80 diameters on periphery)





Double Langmuir Probe	Electrode Diameter [mm]	Electrode Length [cm]	Electrode Spacing [cm]
Probe 1	0.254	5.08	4.45
Probe 2	3.175	12.2	5.72
Probe 3	9.525	19.70	5.72

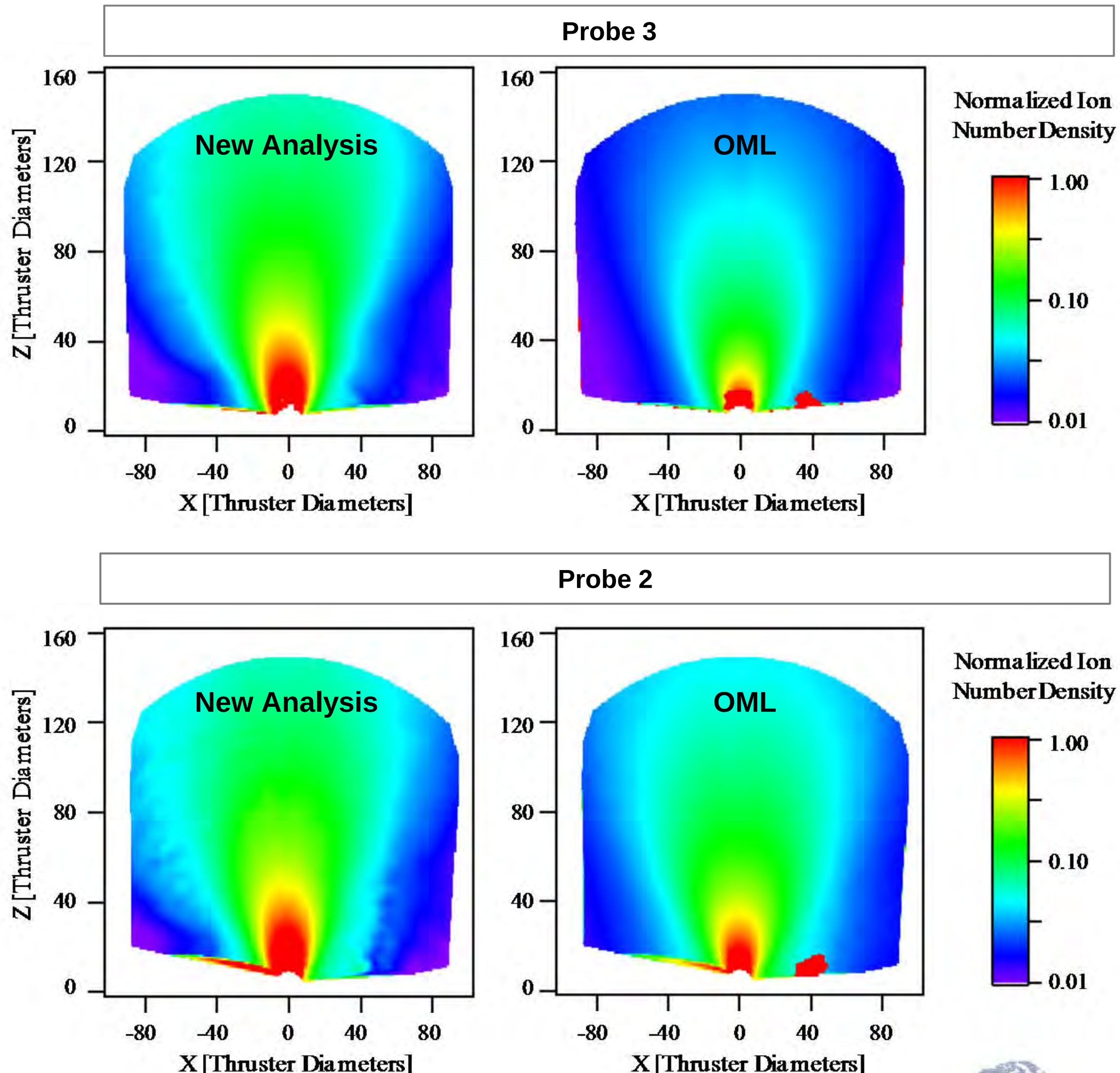


Langmuir Probe Plume Data

Plume Comparison of Probes 2 and 3, $1.3X10^{-6}$ torr-Xe

Qualitative Comparison

- Probe 2 and probe 3 in agreement using new analysis
- Probe 3 shows better agreement on periphery
- Probe 2 shows better agreement in central plume
- Poor agreement using OML theory reveals large uncertainty typical of Langmuir probe measurements (attributed to sheath physics with local plasma)

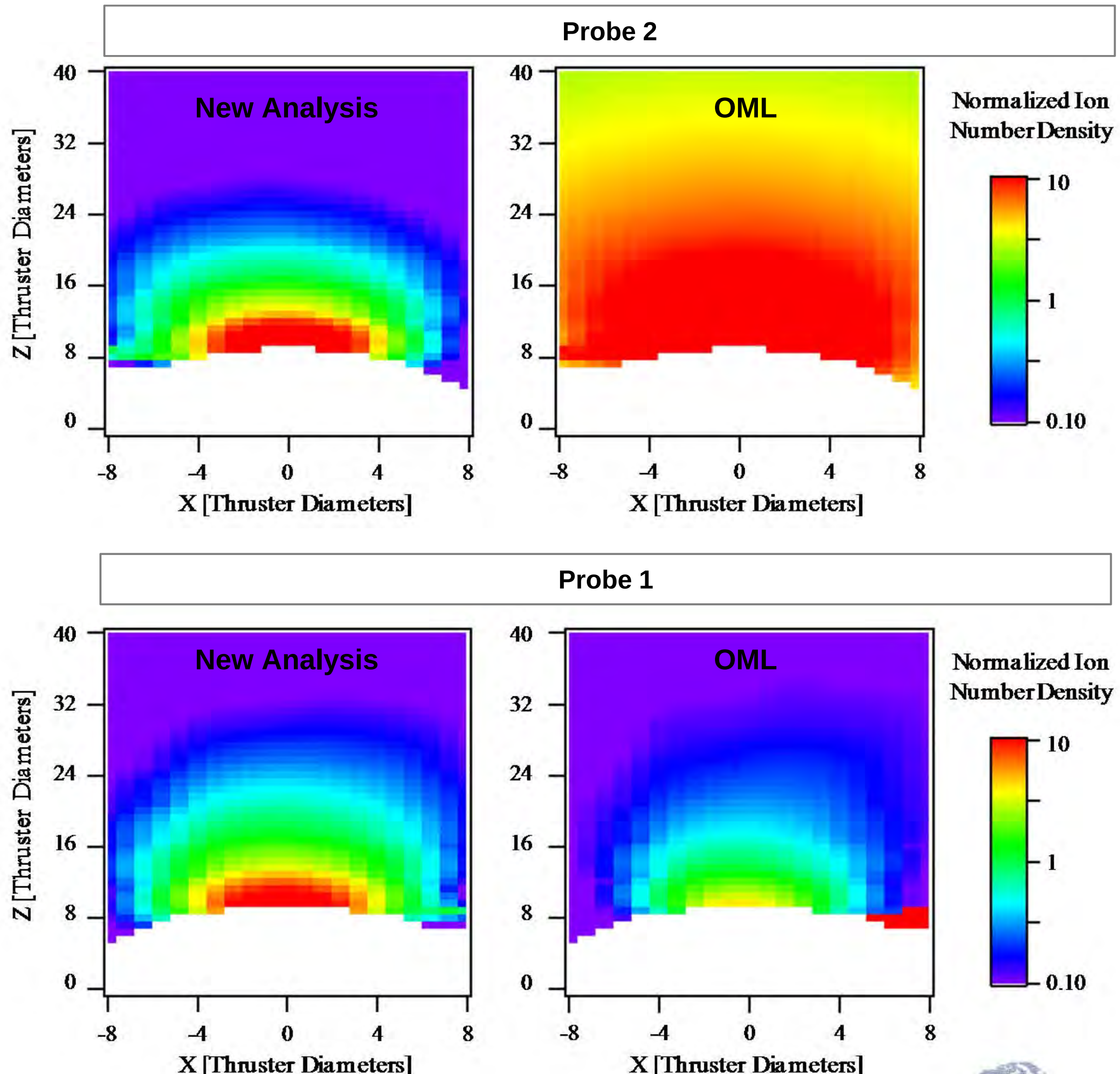


Langmuir Probe Plume Data

Plume Comparison of Probes 1 and 2, $1.3X10^{-6}$ torr-Xe

Qualitative Comparison

- Probe 1 and probe 2 in agreement using new analysis
- Probe 2 shows poor agreement throughout near-field
- Probe 1 shows better agreement in central plume using OML
- Poor agreement using OML theory reveals large uncertainty typical of Langmuir probe measurements (attributed to sheath physics with local plasma)



Langmuir Probe Plume Data

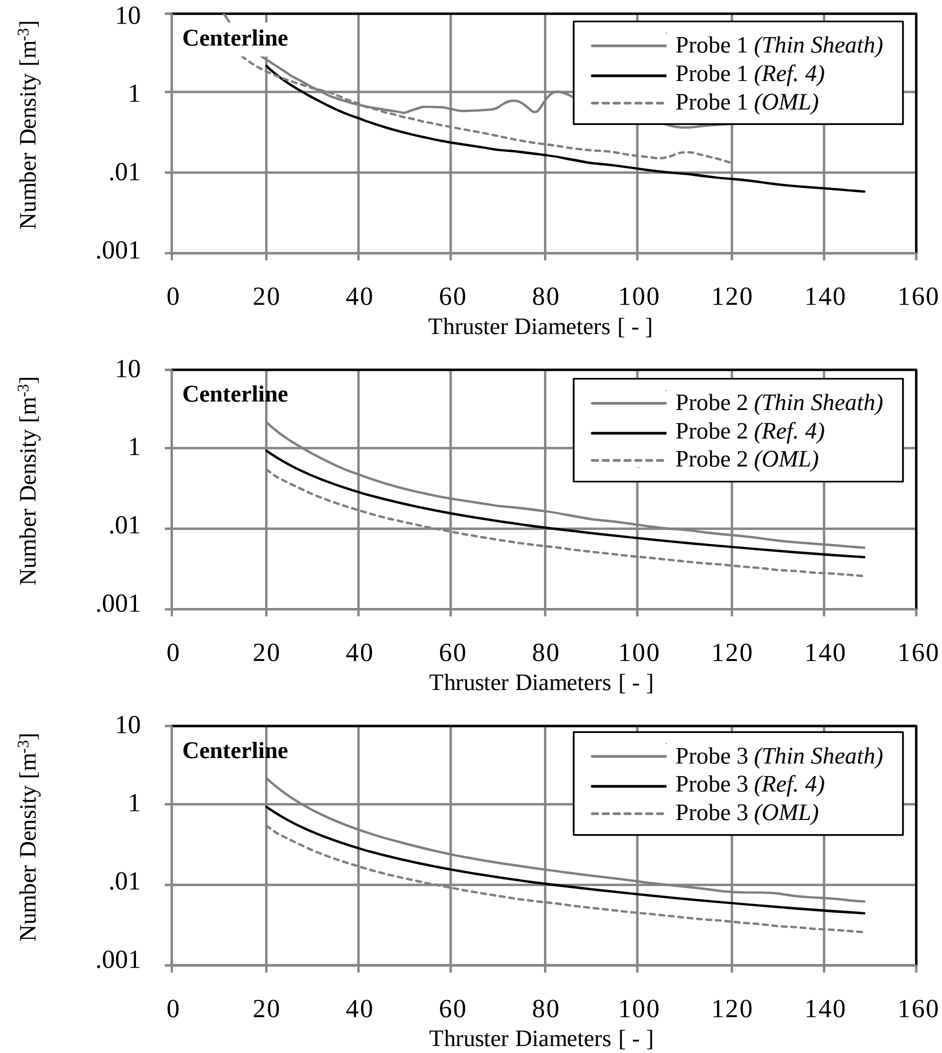
Comparison of Analysis Techniques, $1.3X10^{-6}$ torr-Xe

New analysis consistent with thin sheath in near-field and OML in far-field

Probe 1 not valid in far-field beyond 40 diameters (poor signal to noise for small diameter probe)

Probe 3 not valid in near field due to poor spatial resolution (large probe with length several times thruster diameter)

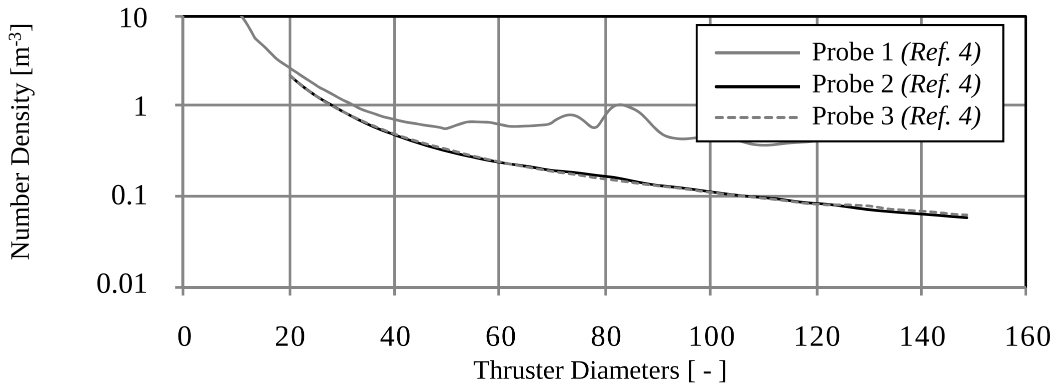
Data shows that a single probe is not adequate to accurately measure full range of properties



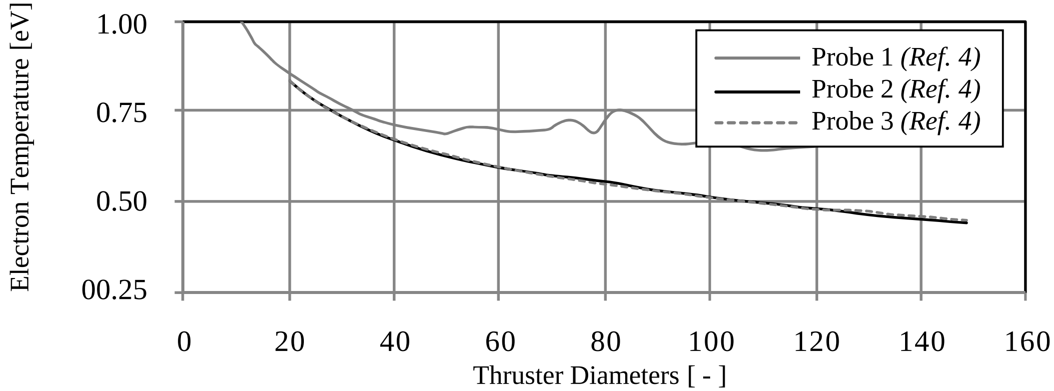
Langmuir Probe Plume Data

Assessment of Technique wrt Probe Geometry, $1.3X10^{-6}$ torr-Xe

Comparison of centerline plasma data indicates new analysis accounts for sheath effects, and matches properties from different probe geometries based on comparison between probes 1-2 (near-field) and 2-3 (far-field) throughout the plume.



Results consistent with past measurements



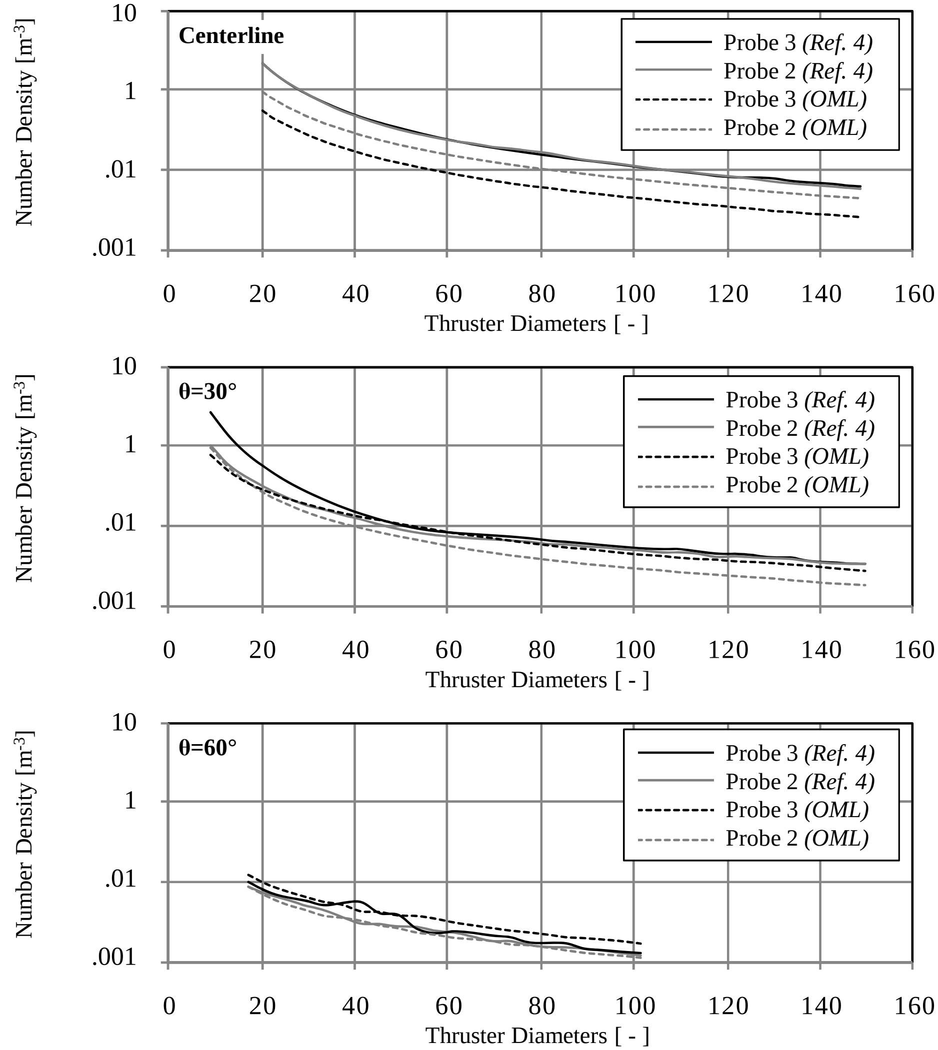
Langmuir Probe Plume Data

Probe 2, 3 at 1.3X10^{-6} torr-Xe, θ=0°, 30°, 60°

Data shows plume scattering and ion migration at approximately 30 degrees off-axis is accounted for with new method (attributed to accounting for sheath effects)

Demonstrates consistent agreement between Probe 2 and 3 throughout the plume

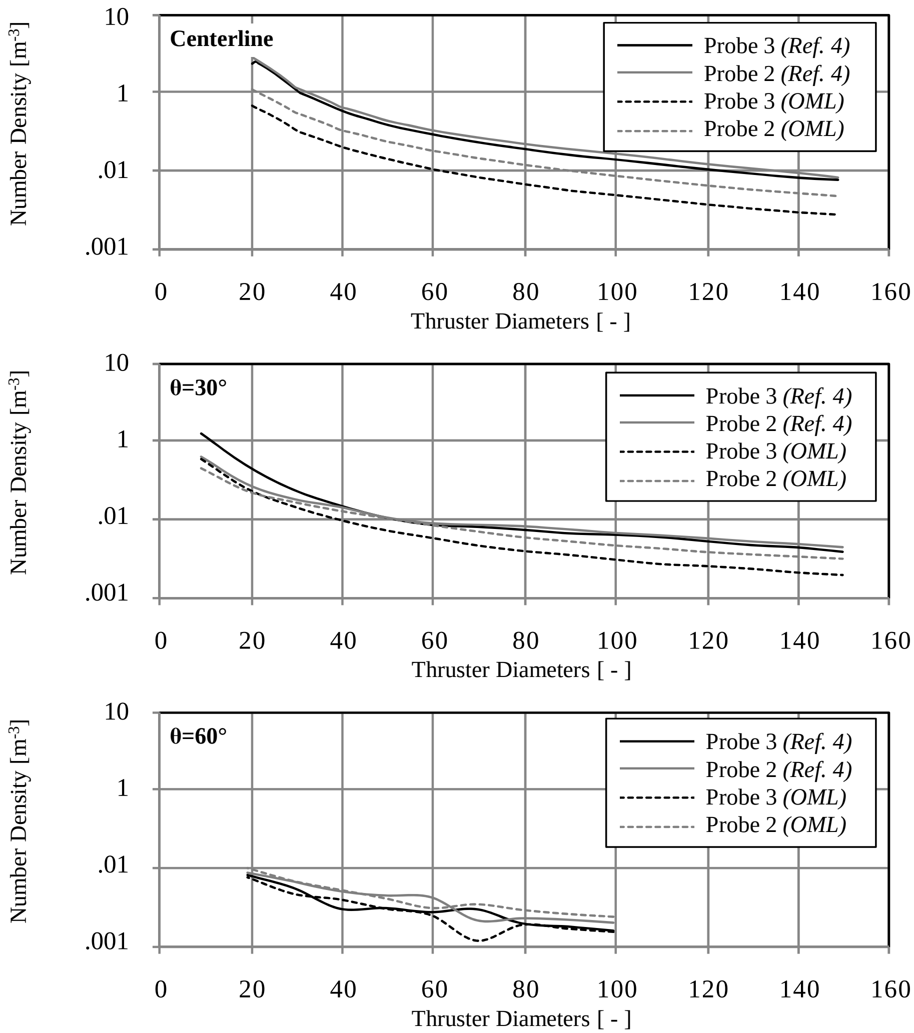
NOTE: Probe 1 did not have adequate signal to noise for comparison at 30, 60 degrees



Langmuir Probe Plume Data

Probe 2, 3 at 4.8X10^{-6} torr-Xe, θ=0°, 30°, 60°

- **High pressure shows new analysis accounts for sheath effects, consistent with low pressure data**
- **New analysis consistently shows agreement in number density within 10%**
- **Future efforts may focus on uncertainty analysis to reduce 50% error bars**



Summary and Conclusions

New double probe analysis technique evaluated with measurement of Hall thruster plume using 3 probe designs

Comparison indicates new analysis technique successfully accounts for probe sheath physics over wide range of r_p/λ_D throughout the plume

Probes show better agreement throughout the plume with new analysis

Analysis advantageous for transition regions between thin sheath and OML analyses

Investigation supports using a fixed probe design with single analysis over a wide range of r_p/λ_D in low temperature plasma